Basics of using precision instrumentation amplifiers in single-supply designs

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Designers now have available a broad collection of instrumentation amplifier (in-amp) design circuits for dual supplies. However, there also is a growing use of the single-supply amps, especially in battery-operated portable systems. Adopting the dual-supply circuits into a single-supply application is not trivial. Designers should never copy and paste dual-supply instrumentation amps into a single-supply. Instead, they need to take special when designing in-amps into single-supply applications.

A difference amplifier is the most primitive in-amp realization, using a single operational amplifier (op-amp) and four resistors, as shown in **Figure 1**:

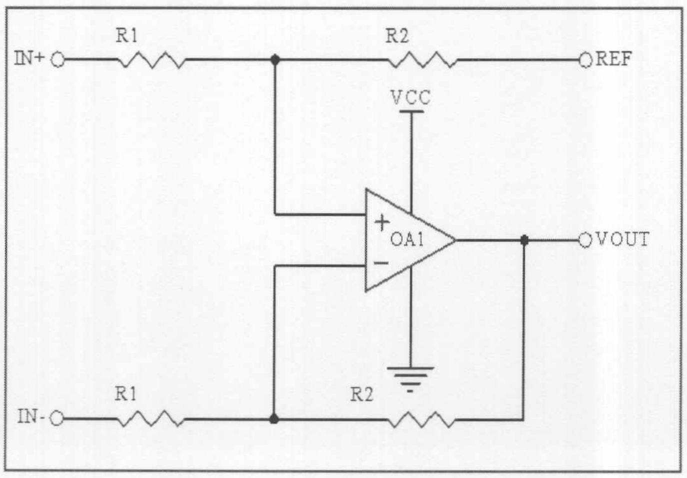

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Figure 1: The basic difference amplifier configuration.

Depending on the input source impedance and the common mode input voltage, the difference amplifier can be designed in a single-supply system with ease. The difference amplifier's performance is limited by its finite input resistance.

Therefore, when high input-source impedance is present, a difference amplifier will load down the input signal. A difference amplifier will be insensitive to common-mode voltages only if the op-amp is ideal and the resistors are perfectly matched. However, no amplifier is ideal, and common-mode rejection ratio (CMRR) is a strong function of the resistor mismatches. Assuming an ideal op-amp and tight

resistor tolerance of 0.01%, the in-amp's CMRR degrades to 72 dB. Nonetheless, it is the only in-amp realization that can sense voltages that are above the supply rails.

As with all in-amps, a REF terminal sets the zero level of the output. Depending on the expected differential input voltage, the REF terminal has to be driven by a low impedance source to maximize the dynamic range of the output. If the expected differential input voltage is only positive (IN+ greater than IN-), then the REF terminal is grounded. For differential input voltage that swings symmetrically across zero, the REF terminal should sit at $V_{CC}/2$.

When the REF terminal needs to be lifted above ground, the most common mistake is driving the REF terminal with a resistor divider. A low-impedance source, such as a buffer or a voltage reference, is needed to drive the REF terminal. Otherwise, the CMRR of the difference amplifier circuit will degrade.

The finite impedance drawback of the difference amplifier is eliminated by preceding it with a buffer, as in **Figure 2**:

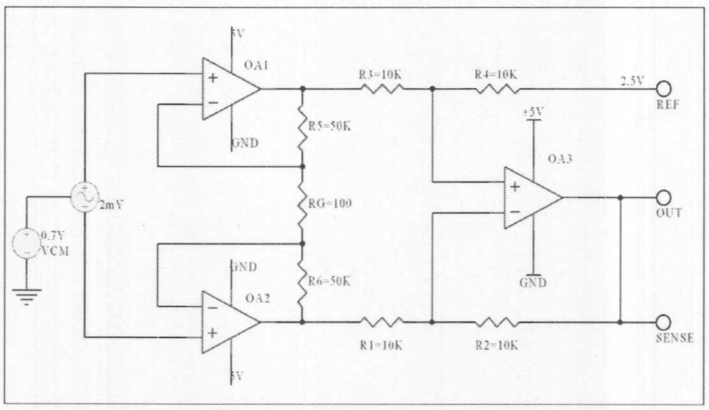

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Figure 2 The AD623 in a three op-amp realization.

This is a classic in-amp realization known as the three op amp in-amp, and has been available in a monolithic IC for years. Manufacturers specify carefully trimmed internal resistors to 50 kΩ and resistor R_G is brought out for gain control. The resulting gain equation is simplified to:

$\text{GAIN} = (1+ 100\ \text{k}\Omega / R_G)$.

This three op-amp realization solves a problem but creates another. The buffer improves the input impedance but significantly reduces the input range of the in-amp.

With three-op amp topology, the user has to be even more careful. It is usually the gain stages OA1 and OA2 where most users get in trouble. These gain stages will saturate when high gains and improper common mode biasing are combined. A balance of common-mode biasing versus gain should be considered.

For example, the three-op-amp in Figure 2 is implemented with a gain of 1000. The expected input is 2 mV_{pp}. The three-op-amp, which is the AD623, has a level shifter integrated to shift the common-mode voltage up to V_{be} (0.7 V). Also, the REF terminal is raised to 2.5 V to achieve maximum and symmetrical positive and negative swing.

The common mode voltage of 0.7 V will also exist at the negative terminals of the OA1 and OA2. The output of OA1 will be:

V_{out1} = 0.7 V + 2 mV * (50 kΩ/100) = 1.7 V.
The output of OA2 will be:

V_{out2} = 0.7 V " 2 mV * (50 kΩ/100) = -0.3 V.
Clearly, the OA2 cannot produce a negative voltage and is saturated. The problem is exacerbated with decreasing supplies and increasing gains.

To improve the headroom of operation without increasing the supplies and without lowering the gain, the common-mode has to be biased right at $V_{CC}/2$. Common-mode biasing involves additional external circuitry and is prone to offset errors. Again, the REF terminal should be driven by a low-impedance source to preserve the CMRR performance.

Figure 3 shows another popular in-amp realization, the two op-amp topology. Simply put, it is a cascade of two inverters with a high input impedance and high CMRR, but with much more carefully trimmed resistors.

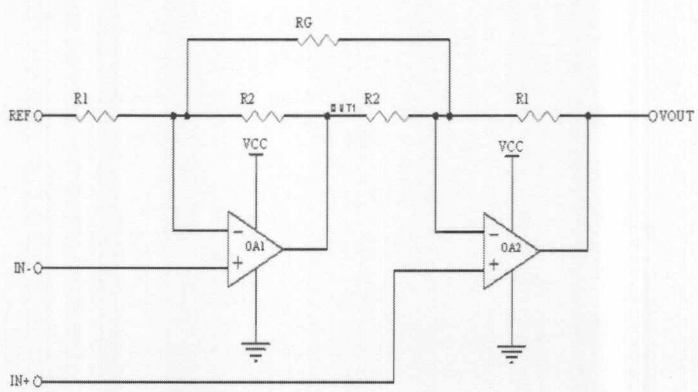

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Figure 3: The INA122 two op-amp realization.

In this case, it will be more difficult to saturate the output of the first OA1, because it is gained by a factor slightly greater than 1:

$V_{out1} = V_{in}$ * (1 + 25 kΩ/100 kΩ) when REF=0 V.

As such, higher gains can be achieved compared to the three op amp counterpart. INA122 is a two op-amp topology and can obtain gains up to 10,000 V/V.

Similar to the three op-amp configuration, the two op-amp design REF terminal has limitations. OUT1 never goes below zero. In order to avoid saturation of OA1 and thus erroneous output voltages, the REF terminal should always be less than $(1 + R_1/R_2)$ times the common mode voltage, V_{cm}. Thus, for ground-sensing applications, a REF terminal should never be lifted above ground. This is a huge disadvantage when the zero level of the output needs to be adjusted.

The best solution is to simplify the design and eliminate additional circuitry associated with

conventional instrumentation amplifiers, **Figure 4**.

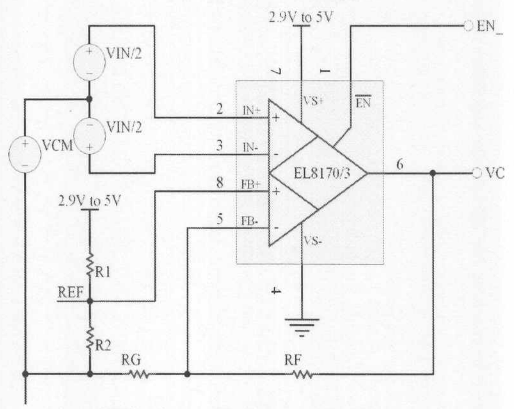

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Figure 4: EL8170/73 in-amp with two pairs of inputs.

This can be achieved by using in-amps that have two pairs of inputs, representing a significant difference from the previous topologies. One of the pairs is driven directly by a differential input signal. The other is driven by a portion of the output. This active input stage is the feedback path, hence the term feedback terminals. The common-mode input can be biased anywhere between or slightly above the supplies, regardless of gains, up to 10,000 V/V. There is no fear in saturating the buffers at high gains, unlike a three op amp design. The in-amps also should have a high-impedance REF terminal, which eliminates the need for an additional buffer.

One example of a device that optimizes performance for single-supply applications is the EL8170/3 from Intersil. A simplified schematic and block diagram for the EL8170/3 is shown in **Figure 5**, to illustrate rail-to-rail operation for both the input and output stages. The same schematic applies to the EL8171/2, but with the PNP transistors (Q_1-Q_4) replaced with P-channel MOSFETs for lower input-bias current.

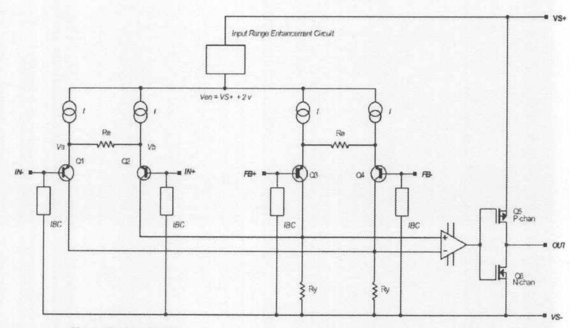

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Figure 5: Simplified equivalent circuit of EL8170.

The input terminals (IN+ and IN-) and feedback terminals (FB+ and FB-) of the EL8170/3 are single, differential-pair bipolar PNP devices aided by an Input Range Enhancement Circuit to increase the headroom of the common-mode input voltage. Likewise, the input terminals (IN+ and IN-) and feedback terminals (FB+ and FB-) of the EL817/2 are single, differential-pair P-MOSFET devices aided by an Input Range Enhancement Circuit to increase the headroom of the common-mode input voltage.

As a result, the input common-mode voltage range of all these instrumentation amplifiers is rail-to-rail, and can handle input voltages that are at, or slightly beyond, the supply and ground, thus making these in-amps well suited for single 5V or 3.3V low-voltage-supply systems. This eliminates the need to move the common-mode input of the in-amps to achieve symmetrical input voltage.

One of the benefits of a device like this is its ability to sense voltage dynamically at both rails, at high gains. **Figure 6** is an elegant circuit simplifying current sensing for motors using H-bridge drive.

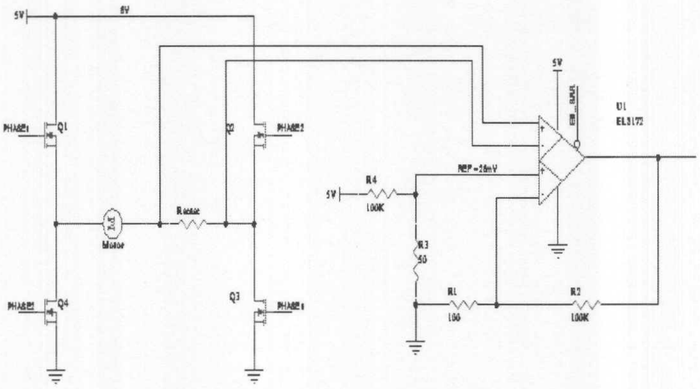

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Figure 6: H-bridge using current sensing

During Phase1, when Q_1 and Q_3 are on, the common-mode voltage is close to ground. During Phase, when Q_2 and Q_4 are on, the common-mode voltage is close to 5 V. The EL8172, one of the members of the EL8170 family, ignores these common-mode voltage variations but amplifies a differential voltage 1,000 times. A simple and economical resistor divider sets the REF terminal to 25 mV, thus setting the zero level to 2.5 V and improving the dynamic output range. When the output voltage is less than 2.5 V, the motor is accelerating in one direction. When the output voltage is more than 2.5 V, the motor is accelerating in the other direction.

Intersil's new family of instrumentation amplifiers are optimized for single-supply systems. The EL8170 and EL8173 are single in-amps with the bipolar input stage, featuring lower 1/f corner frequency than the EL8171 and EL8172. However, the EL8171 and EL8172, with the MOSFET input stage, have virtually no input bias current and are well-suited for extremely high source-impedance applications. Dual and quad versions of these in-amps are also available from Intersil.

About the author
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